LHC PARTICLE COLLIMATION WITH HOLLOW ELECTRON BEAMS

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Abstract

Electron lenses built and installed in the Tevatron have proven themselves as safe and very reliable instruments which can be effectively used in hadron collider operation for a number of applications, including compensation of beam-beam effects [1], a DC beam removal from abort gaps [2], and as a versatile diagnostic tool. In this article, we – following the original proposal [3,4] – consider in more detail a possibility of using electron lenses with hollow electron beam for ion and proton collimation in LHC and the Tevatron.

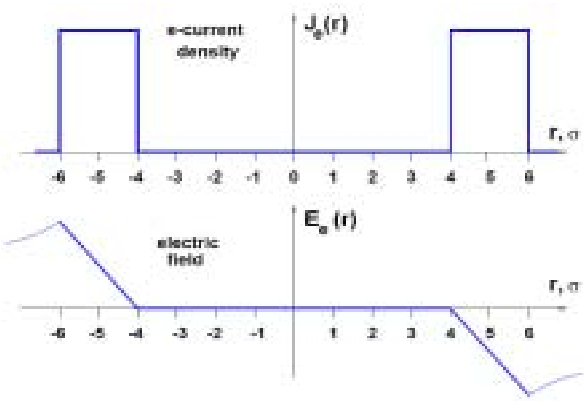

Figure 1: (top) current distribution in the e-lens for collimation; (bottom) electric field of a hollow e-beam.

COLLIMATION BY ELECTRON BEAMS

As depicted in Fig.1, an ideal round hollow electron beam has no electric or magnetic field inside and has strongly nonlinear fields outside. The speed of diffusion of the large amplitude particles (protons or ions, in the case of LHC, which traverse the non-zero electric field region) can be greatly enhanced if the electron current varies in sync with betatron oscillations or at the nearest non-linear resonance line. The hollow e-beam can increase impact parameter on existing primary collimators, or serve as EM primary collimator or as an enhancer – a device for faster delivery of halo particles to secondary collimators which can be then placed further from the primary one and the beam itself. Hollow electron beam collimator (HEBC) also offers a viable solution for a primary collimator of the LHC *ion* beams, because such an electromagnetic collimator does not break an ion into fragments (as any primary collimator made of usual material would do). In that case, the hollow e-beam systems would have to be installed to replace the current primary LHC collimators.

Main parameters of the HEBC needed for EM collimation of ions and/or protons in the LHC are presented in the Table below. For comparison, the TEL electron beam parameters are j_e=6 A/mm^2, B_m=6.5T, P_{coll}=50kW – i.e. the hollow e-beam parameters are not very far from those already achieved. Placing the HEBC system some 100 m away from IPs, in the location of very large beta-functions between D1 and D2 magnets, has an advantage of needing comparatively large electron beam radius because of large beam size at these locations σ≈1.1 mm. Other, m.b. more suitable locations for the HEBC in the betatron or/and momentum cleaning long straight sections (where the Phase I collimators are located) could be used as well. The beam size in these locations with smaller beta-functions, is about of 3-4 times smaller and a hollow electron beam size (which is some 4-5σ inner radius) has to be smaller, too. A compression ratio of the electron beam emitted by a ring cathode should be proportionally higher, that calls for higher ratio of the magnetic field in the interaction region and on the cathode B_m/B_{cath}. Minimum field on the cathode depends on the electron current density (the field should be high enough to keep the electron beam stable against its own space-charge forces). Maximum field in the main solenoid is limited by technology (and is about 12-15T). Although higher B_m/B_{cath} ratio will make e-collimator design quite different from TELs (compared to the high-beta location HEBC), the electron beam formation and dynamics as well as magnet design will not go beyond a well established technology.

Maximum electron current	10-50 A (~3 kHz *AC*)
Electron beam energy	10-25 kV
Electron beam length	2(4)m
e-beam radius/width @e-IR	Hollow4.4mm/1.1mm
Ring cathode radius/width	25 mm/ 6 mm
B-field main/cathode /collector	32/1-2 /1 kG
Current density on cathode	j_e=1-5 A/mm^2
β–functions @ e-IR location	$\beta_x = \beta_y$ =2300 m
Beam power in collector	P_{coll}=20-50 kW

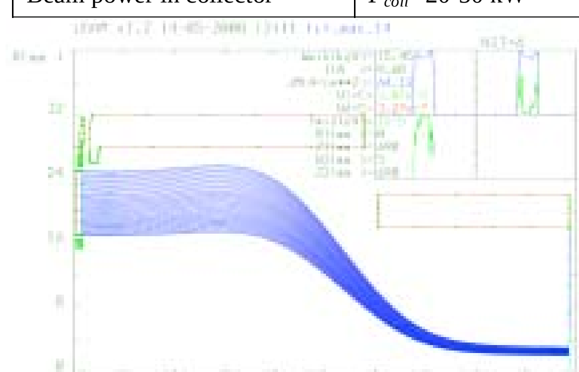

Figure 2: UltraSam simulation of the hollow electron beam gun for LHC collimation.

A possible design of the electron gun with magnetic compression provided by two solenoids are depicted in Fig.2. The layout of the HEBC system needed for generation of the axially symmetric hollow electron beam for the LHC beam collimation is shown in Fig.3.

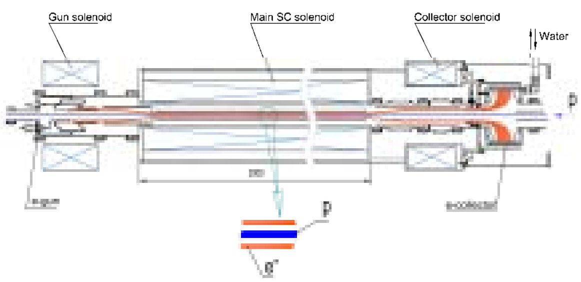

Figure 3: Electron lens configuration for collimation

MODELING FOR LHC

Fig.1 shows the geometry of the radially symmetric hollow beam used in the model. The transverse (radial) angle kick provided by the low energy electron beam with inner radius r_{min} , electron velocity $\beta_e=v/c$, total current J_e, and total length of L is equal to:

$$\Theta(r)=\Theta_{max}\begin{cases}0 \quad if\ r<r_{min}\\ \frac{r-r_{min}}{r_{max}-r_{min}}, r<r_{max}\\ \frac{r_{max}}{r},\ r>r_{max}\end{cases} \quad \Theta_{max}[\mu rad]=\frac{0.2L[m]J[A]}{(B\rho)r_{max}}\cdot\left(\frac{1+\beta_e}{\beta_e}\right)$$

where $B\rho$=2.3*10^4 Tm is magnetic rigidity of the 7 TeV LHC beam. E.g., the dipole kick produced by 2-m long 10kV 10A beam at r_{max}=6σ (6.6 mm) is about Θ=0.16 μrad, equivalent to $\beta\Theta$=0.370mm or σ/3 in the betatron amplitude. Maximum kick by a more powerful 50A 30kV 4 m long beam is Θ=1.06 μrad For comparison, the rms angle due to particle scattering in 0.6 m long carbon jaw of the LHC primary collimator is about of 3.4 μrad. The Advantage of the HEBC is that it does not destroy any particle and operates during many turns. Every time when particle appears beyond the boundary of the electron beam, it gets a radial kick.

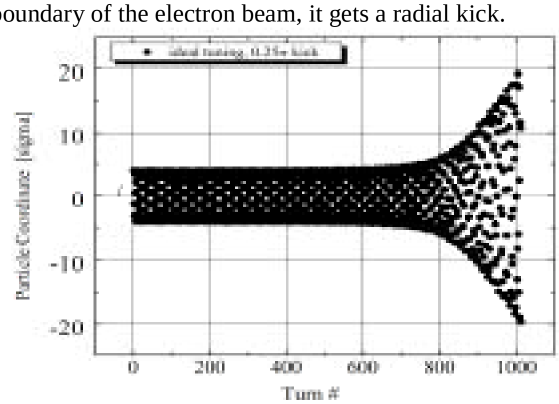

Figure 4: LHC proton motion driven by HEBC with amplitude of Θ=0.25σ modulated at the tune line $Q=0.31$.

In a 1D single particle simulation run [4], presented in Fig.4, a 7 TeV proton which initially intercepted the e-wall boundary by 0.1σ was driven resonantly to amplitudes as large as 10-20σ in less than 1000 turns (0.1 sec of real time in the LHC). A maximum strength of the e-beam kick was equal to 0.25σ. The electron current was modulated in phase with particle's betatron motion (tune of $Q=0.31$).

Due to natural tune spread (induced by beam-beam, or due to synchrotron motion), one should not worry about exact synchronization of frequencies and phases with all the particles. Electron beam modulation frequency can be set close to the frequencies of interest (e.g, frequency of 4σ particles) or may cover a band of frequencies.

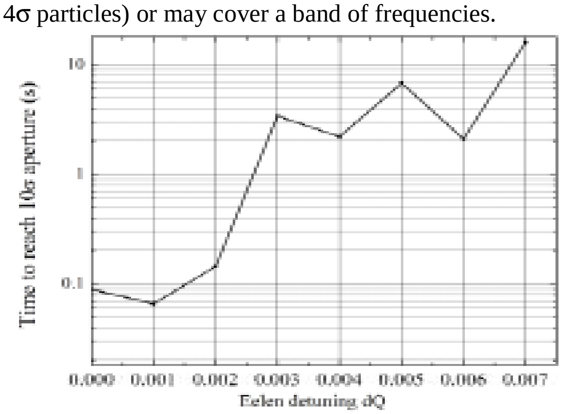

Figure 5: Collimation time (time needed to reach 10σ amplitude) vs detuning parameter dQ.

Figure 5 shows that the time needed (in the simulations) to reach 10σ-amplitude grows with the detuning $dQ=Q_{HEBC}-Q_{betatron}$ and reaches 10 seconds for $dQ=0.007$. For most optimal operation, one can envision detuning not exceeding $dQ=0.002$ which collimates (drives particles out on aperture set by secondary collimators) in about 0.1 seconds. Obviously, with higher e-beam current the collimation time can be reduced as shown in Fig.6. If the secondary collimators are set closer to the beam – say 6-8σ - then, the time will be shorter, too.

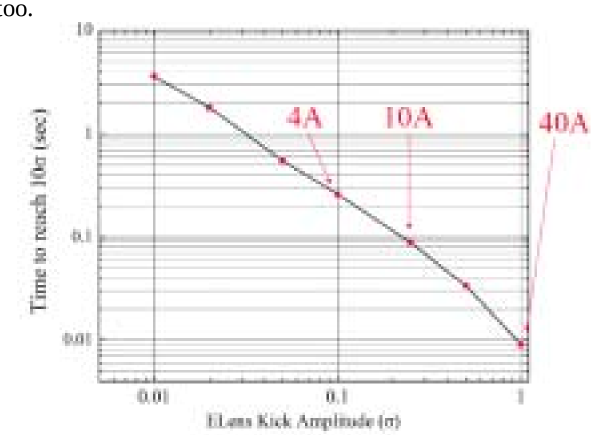

Figure 6: Collimation time (time needed to reach 10σ amplitude) vs maximum electron beam kick.

MODELING FOR THE TEVATRON

More realistic 3D 4000-particle simulations of HEBC have been performed for the Tevatron Collider Run-II lattice which includes electrostatic separators, RF cavities, sextupole correctors, and ~~c~~current position of the collimators [5]. The betatron tunes are $Q_{x,y}$ = 20.582/20.574, the synchrotron tune is Q_s = 0.0007. Initial particle amplitudes are ranging in A_x = (5−5.5) σ_x and A_y = (0.2−0.5) σ_y for collimation in horizontal plane, and similarly in the vertical one. The hollow electron beam with r_{min} = 5σ = 2.9mm and wall thickness of 1 mm is located in the middle of AØ where β_x=108m≈β_y= 98m. The electron current varies with turn number n as $J\cos(2\pi n/P)$ with period P equal to 12.45 turns in horizontal and 6.85 turns in vertical planes.

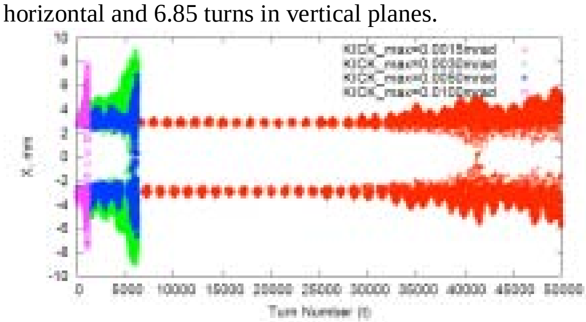

Figure 7: Particle motion in the Tevatron with various max kick values of the HEBC (1.5 – 10 μrad).

Fig.7 shows that depending on the strength of the HEBC, protons are extracted to the secondary collimators at different rates, e.g. 85% of the halo particles were collimated during 10,000 turns with the angular kick strength of 3 μrad.

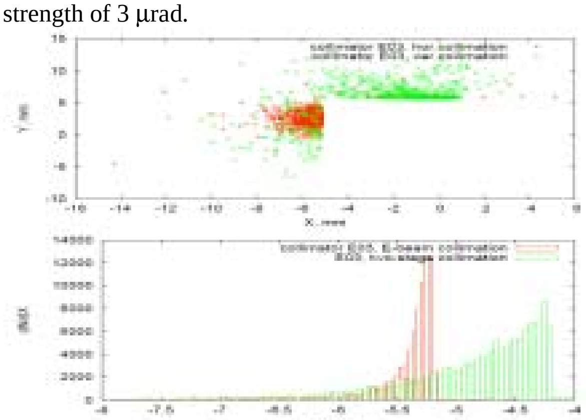

Figure 8: Distributions of particles lost on E03 secondary vertical and horizontal collimators.

Beam population (top) and histograms (bottom) in the secondary E03 collimator at collimation in horizontal and vertical plane with 3 μrad strong HEBC are compared in Fig. 8 with standard 5-mm thick W primary collimator which scatters with the rms angle of 25 μrad. In both cases, the distributions are sufficiently good to assure a low probability of particle out-scattering from the collimator jaws - the impact parameter is ~2.5mm for 2-stage collimation and ~1mm for HEBC.

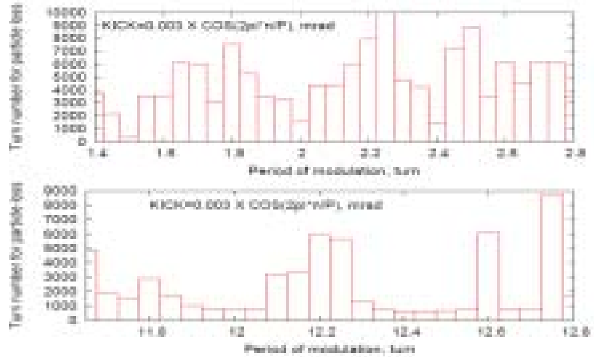

Figure 9: Removal time vs e-modulation period P.

The particle removal rate greatly varies with current modulation period – Fig.9 presents the scans *over* P=1.4-2.8 turns (top) and P=11.6-12.8 turns (bottom).

DISCUSSION, SUMMARY

The hollow electron beam collimation offers a number of advantages compared to standard schemes: a) it works for both ion and proton beams due to its purely electromagnetic nature (no nuclear interactions); b) the HEBC allows to reduce the machine impedance either by replacing primary collimators or placing them farther away from the beams; c) e-beam is “refreshable”, no beam incident can damage it, in contrary of using metal or carbon collimators; d) thus, no expensive damage diagnostics is needed; e) the e-collimator’s size/position are controlled by magnetic fields, and needs no mechanical system (movers, bellows, etc) is needed; f) the HEBC offers control over speed of the particle removal needed to achieve “smooth” removal (no spikes in loss rates) – that is very desirable for collider operation [2].

As shown above, e-collimators are strong enough for fast and effective removal of LHC halo particles. The HEBC technology is similar to that developed for the Tevatron Electron Lenses and the reliability of such a system has been proven by years of operation under a hadron collider conditions.

Future simulation work needs to address the effects of the electron beam imperfections and realistic modelling of the LHC HEBC.

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